# 2. Methods

***Need for a Another Research Approach***

The preceding chapter shows that current prostheses are either cosmetic or functional, evident in three prosthetic archetypes: myoelectric, body-powered and passive prostheses. The results of many previous research projects have improved on these archetypes but have not shown a successful means of combining cosmesis and functionality in a single device, which is desirable for the amputee (Fraser 1998, Sauter 1991).

New developments from research into actuation and control appear to provide key elements for a new generation of artificial limbs that might combine cosmesis and functionality (Della Santa et al 1997).  What is missing, in these developments, is a mechanical ‘platform’ demonstrating how these advancing technologies might eventually be combined and practically applied to the field of upper-limb prosthetics to form a much closer replacement for a lost limb.

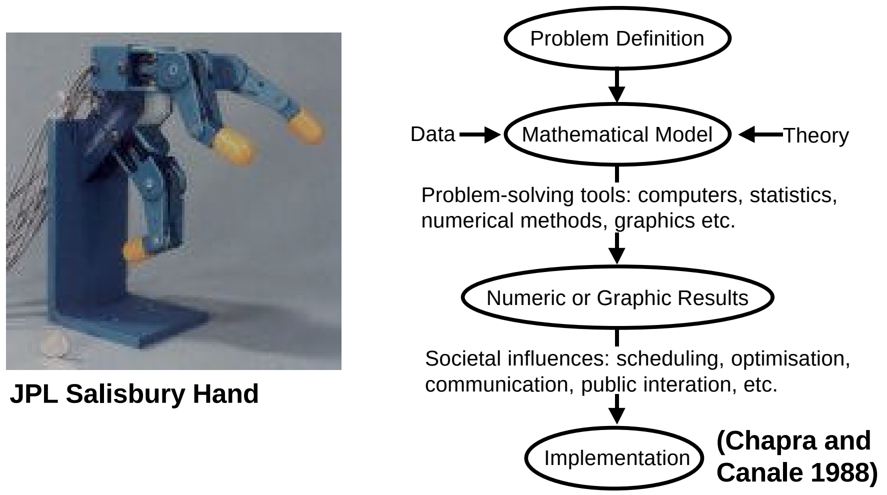


**Fig 2.1 The JPL/Salisbury Hand and an Example of an Engineering Design Method from the Same Period**

In seeking an appropriate form for such a mechanical platform, conventional engineering design methods, used in previous prosthetic research, may be inappropriate. These methods are used as  many of the tasks given to engineering designers are subdivisions of a larger whole (Pitt 1973). Therefore, using 3D structural analysis and other analytical techniques a component can be designed to meet a given specification (Papalambros and Wilde 1991).

However, such methods have not revealed new archetypal prosthesis designs (Banerjee 1982).   Similarly, in the field of advanced robotic hands, the application of optimisation methods has not revealed archetypes that combine cosmesis and function (Mason and Salisbury 1985).  To illustrate this, figure 2.1 shows the JPL / Salisbury Hand and an engineering design method of a similar period.  This hand was developed using mathematical techniques to design a dextrous manipulator with an optimal kinematic configuration of joints for grasping objects (Mason and Salisbury 1985).  However, it can be seen that this method has resulted in a device very mechanistic in appearance, which arguably would be cosmetically unacceptable to the amputee.

Thus, methods focussing on optimisation have failed to combine cosmesis and function and a methodology is required that can elicit appropriate new design principles.

***Creative Reasoning***

Amputees need to carry out normal activities of daily living and so must live and work in the common environment, using everyday products and controls (levers, handles etc.) which have been designed around the anthropometric measurements of the typical human hand (Croney 1980). Therefore, a new approach drawing reference from the human hand appears appropriate. In fact recent studies have indicated that it is essential to observe the human hand closely before embarking on the design of a prosthetic or robotic hand, and have stated it *presumptuous* not to do so (Pons et al 1999, Pieffer 1996).

However, drawing clear design principles appropriate for a robotic or prosthetic device from the complex biological upper-limb is complicated by the subtleties and individual variations of the highly complex biological forms of the human hand (Landsmeer 1976). A method is needed that enables appropriate analogies to be extracted from the study of the human upper-limb, whilst not becoming overwhelmed by its subtlety and complexity.

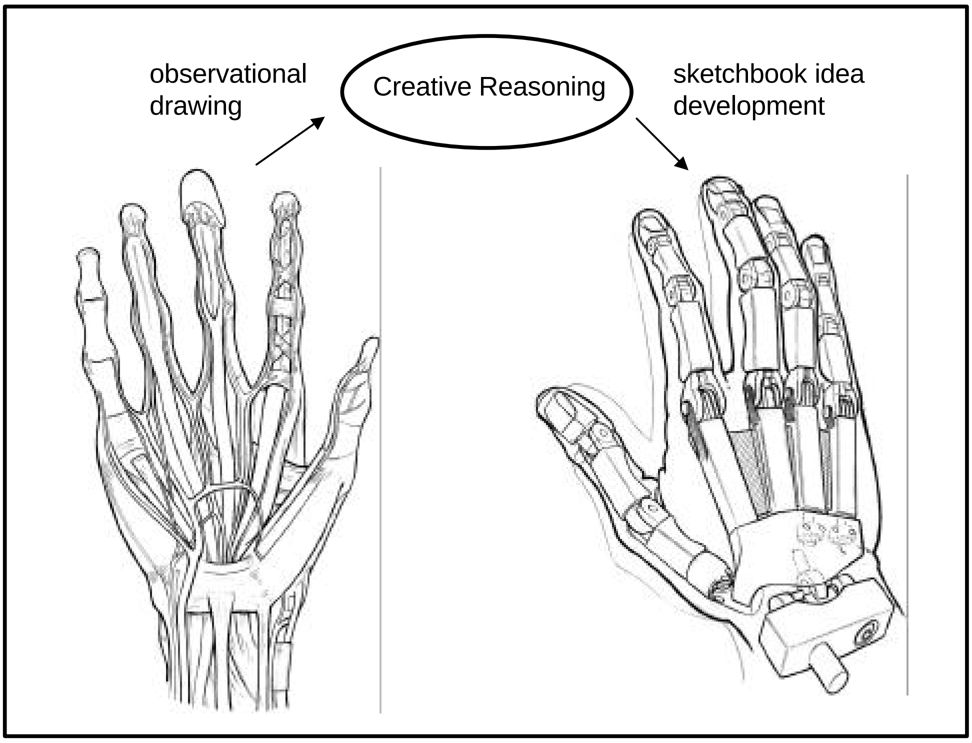


**Fig 2.2 Drawings of a Human and a Mechanical Hand**

The research method chosen is a form of practice led design research as described by Archer (1995). This places emphasis on creative activity during analysis stages in order to *'shed light on the problem'* (Archer 1995). Within this research project the term 'creative reasoning' has been adopted to describe the stage within the research process when new analogous ideas are generated. The techniques used focus on the close scrutiny of the anatomical hand through 'observational drawing' and 'sketchbook idea development'.

### *Creative Reasoning*

It has been indicated that, through the production of detailed life drawing, the 'producers' three-dimensional knowledge of the subject is enhanced (Simpson 1973). Detailed life drawings made to identify and understand subtleties of human form have a long history and clear examples can be seen in the Renaissance. During this period artists such as Andrea Verrocchio used life drawing studies of the human to enhance his knowledge of human musculature (Conrad *et al* 1995). The technique of detailed drawing made from human anatomy is also profoundly important in the history of medicine (McGrew 1985). Leonardo DaVinci, who studied under the supervision of Verrocchio, applied the method of detailed drawing to, not only surface musculature, but also the study of dissected human cadavers (Conrad et al 1995).

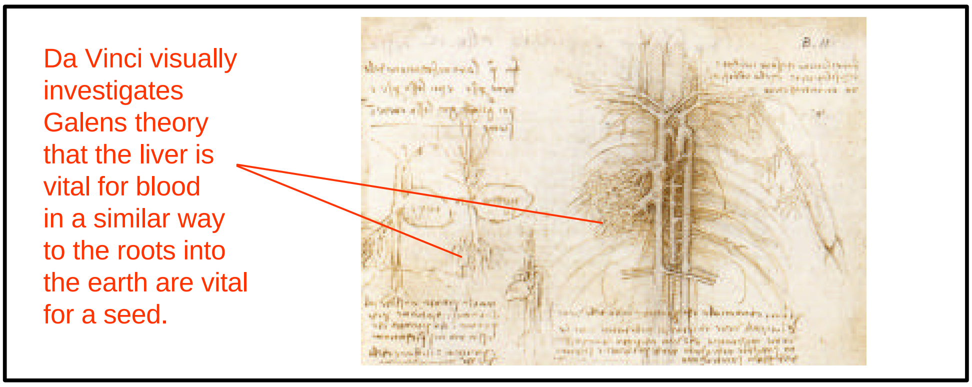


**Fig 2.3 A Leonardo Da Vinci Anatomical Study**

This process has been referred to as 'observational drawing' within this research project. A stage of observational drawing from three-dimensional skeletal anatomical models has been included as a primary research activity to inform subsequent detailed design work. The drawing techniques used in the main body of the work record shape through delineation, form by hatching techniques and dimensional annotations are added to record scale information. However, observational drawing is not exclusively used in the creative reasoning process. It is combined with reviews of anatomical literature to inform the process of functions of the limb which are not apparent from the study of static three-dimensional limbs.

The subsequent stage in the creative reasoning process is the generation of sketch book ideas. This uses the enhanced knowledge of the limb gained through observational drawing to inform sketches that identify parallels between the complex observed anatomical forms and those of more simple geometrical forms . This has been referred to within this research project as 'sketchbook idea development'. Previously this technique has been used by the anatomist Kapandji for educational purposes. He uses drawings of geometrical forms alongside drawings of the anatomy in his anatomy text books to highlight functions and forms of the anatomy (Kapandji 1982).

Figure 2.3 shows sketch book comparisons made by DaVinci in the time of the Renaissance showing the main arteries of the thorax against compared to a sprouting seed. Through this visual comparison DaVinci questioned Galen's assertion that the liver was the vital organ for the blood (Gombich et al 1989).

Observational drawing and sketchbook idea development are combined with literature review to form the inputs to the process of creative reasoning used to develop skeletal joints analogous to those of the human limb.

### *Analogy*

This research is concerned with investigating mechanical analogies to the biological joints of the limb. Because it appears unlikely that whole biological limb grafts will be feasible in the medium term (Lee *et al* 1999), it is argued that such analogies offer the most promising route to a replacement limb which can match the appearance and function of the original. Such an artefact will never be the same as the human limb, however, it might express a likeness.

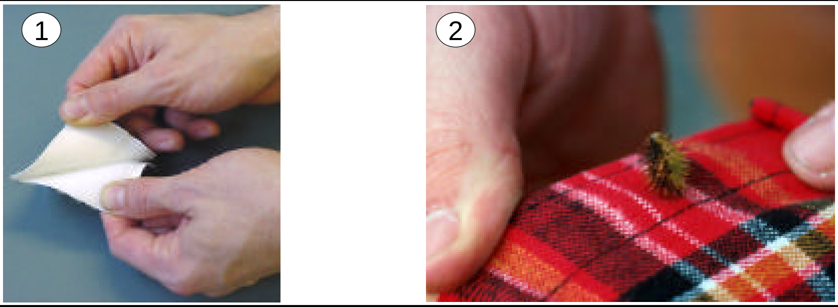


**Fig 2.4 Velcro $^{R}$ (1) Inspired by the Cocklebur Seed (2)**

In language, analogies are used to express likenesses or parallels to clarify or simplify thoughts or concepts. In design and engineering analogy is used as a primary tool to find solutions to problems that may have been previously addressed in other fields or in the natural world (Papanak 1972). Analogy as a means of stimulating new ideas has been described as the most powerful concept (Pugh 1990), and the 'staple diet for the would be inventor' (Thring and Laithwaite 1977).

There are many examples of analogy in design and engineering being used to solve practical problems. '*Sir Marc Isambard Brunel when designing the first river tunnel across the Thames in 1843 conceived the idea of caisson from observing ships worm tunnelling in wood'* (Pugh 1990). The underslung chassis is evident in the insect world, spiders and beetles utilising the lowered centre of gravity to prevent themselves from falling on their backs, as they would not be able to 'right' themselves (Thring and Laithewaite 1977). Figure 2.4 shows how the invention of Velcro was inspired by the observation of the properties of the cocklebur seed (Papanak 1980).

Whilst the use of analogy is very powerful, care needs to be taken to identify the original context of the subject for the analogy. For example, it is important to be aware of the effects of scale. Although mass varies with the cube of the dimensions, strength varies with the square of the cross section (Gordon 1978), therefore, some structures may not be appropriate for direct replication at differing scales (Steadman 1978). Other phenomena have been found to be similarly 'context sensitive'. This has been evident in the field of 'artificial muscle' research. Rapid, powerful dimensional changes of polyacrylonitrile fibres stimulated by diffusion of acids and bases show promising performance at small scales (Shalenpoor et al 1996). However, such fibres cannot be similarly arranged to make useful large scale artificial muscles as diffusion of the actuating chemicals into the larger structures is much too slow (Brock and Lee 1994).

However, design principles based on a skeletal analogy of the human limb appear extremely appropriate, as the resulting design ideas will be embodied at a similar scale to those observed. This is important as the inherent mechanical properties of the observed forms will be appropriate to those of an upper-limb prosthesis using the appropriate choice of materials.

***Need for Physical Models and their role in Evaluation***

Creative reasoning may produce drawings pointing to apparently appropriate analogies of the articulations of the human limb. However, it is important to recognise that they still represent abstractions. Therefore, a stage of model making is an integral part of research which uses practical design methods.

Skilled drawing can mislead both the observer and creator into believing that a mechanism will function when, in fact, it may be fundamentally flawed. Examples of this problem may be seen in the multitude of sketches of perpetual motion machines (Laithwaite 1980). A second pitfall is the appreciation of scale. This is evident in Leonardo DaVinci's ornithopters. Whilst these sketches contain similar forms to those observed from birds they contained no appreciation for the escalation of mass of the structure for it to withhold a human (Gibbs-Smith 1978).

Therefore, the production of physical models permits the design concepts to be tested against reality. In the case of a model developed to be a close skeletal analogy of the human arm; this can be demonstrated in the use of conventional goniometric techniques used to assess the range of movement of the proposed joint designs (Norkin and Joyce-White 1995).

Researchers investigating the nature of the human peripheral nervous system have used a similar method of physical model development to test theories of the reflex nature of human limb movement. For although numerous reductionist experiments have elucidated many aspects of human motor control it is impossible to form a whole picture of human motor control without embodiment into a physical test rig (Hannaford 1995). Similarly, previous work on the development of robotic hands has indicated that the activity of producing of a physical model enables many of the underlying theoretical problems to be more clearly understood. (Jacobsen et al 1984).

The complexity of the human limb suggested that an iterative method based on the production of physical models and prototypes and their subsequent evaluation would lead to an increasingly refined analogy. Fig 2.5 gives an overview of the methods adopted in this research

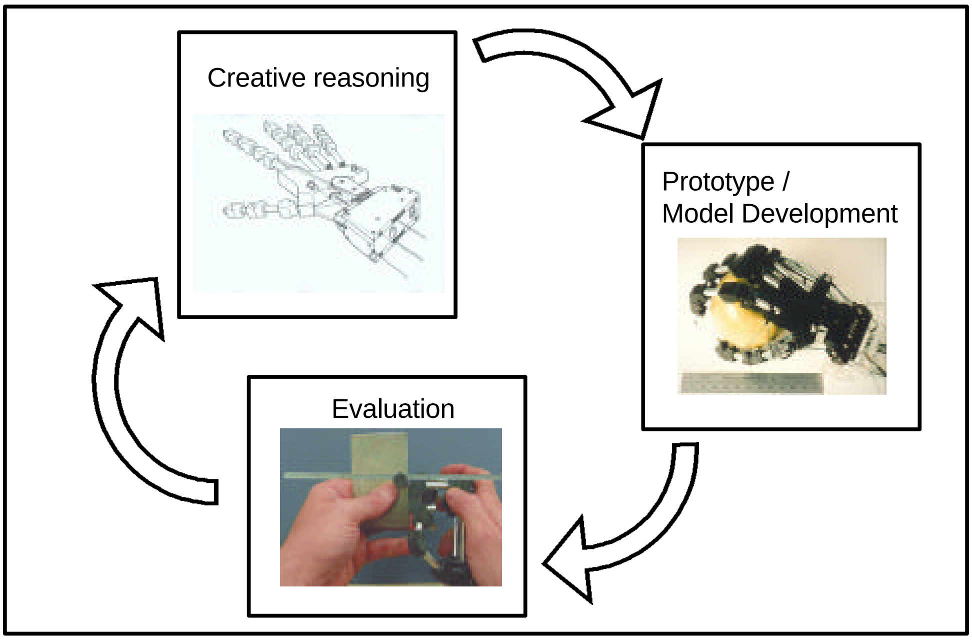


**Fig 2.5 A Form of Practice Led Design Research**

***Need for Physical Models and their role in Evaluation***

Another key aspect of the production of physical models in this research is their use as a tool to stimulate criticism from the end-users. The production of physical models permits criticism of the design by a wide range of interested parties at many levels, both qualitatively and quantitatively.

The end-users in this research project are primarily people with absent limbs, however, prosthetists, occupational therapists and prosthetics manufacturers are also ‘users’ as they too are affected by the design of prostheses. Therefore, an amputee support group has been attended on a regular basis to review the research as it has developed and to gain an understanding of the experiences and concerns of a group of users.

**Fig 2.6 End-User - Focus Group** (taken from the current research)

The analogous models produced within this project are skeletal analogies, without a soft tissue covering. This indicates that direct comparisons between measurements of the intact human arm may be difficult. To overcome this problem, qualitative evaluation of models by professionals with good anatomical knowledge have formed an important part of the review process.

Designers of the influential myoelectric prosthesis, the 'Utah Arm', recognised that, due to number of criteria necessary to evaluate a new artificial arm design, trial and review by experts was essential (Jacobsen et al 1982). However, a research process conducted through the development of physical models can take this a step further, inviting evaluation *during* the design process and allowing the results to feed into subsequent development. Previous research aimed at challenging the state of the art of prosthetic or robotic hands has resulted in laboratories creating complete systems (Jacobsen et al 1984). However, evaluations of such complete robotic systems have indicated that it is perhaps more appropriate to invite the criticisms at an earlier stage rather than attempt complete systems (Perlin et al 1989).

Physical model and prototype construction therefore plays a central role in the work described in this thesis. These models and prototypes provide a practical means of gaining both valuable evaluative data and as a means to link with other researchers specialising in areas such as actuation and control. Additionally, it was thought that dissemination of knowledge, not only through publications, but through physical models provides a practical demonstration of the challenges still faced in applying new technologies to the field of prosthetics.